Cross section for the reaction $\bar{\nu}_e + p \to n + e^+$ and fundamental characteristics of the weak interaction

L. A. Mikaélyan, M. D. Skorokhvatov, and A. V. Étenko
I. V. Kurchatov Institute of Atomic Energy, Moscow

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A "worldwide average" value has been found for the cross section for inverse β decay for reactor antineutrinos: $\sigma^{\text{expt}} = 6.32 \times 10^{-43}$ cm^2/fission (^{235}U) $\pm 3.3\%$. The axial constant has also been found: $g_A^{\nu p} = (1.78 \times 10^{-49} \pm 2.6\%)$ erg·cm^3. This value agrees with the value found for the constant g_A^n from neutron decay: $g_A^{\nu p}/g_A^n = 1.00 \pm 2.8\%$. The polarization of the neutrinos, $h_\nu = 1.00 \pm 4.7\%$, agrees with the absence of right-hand currents.

1. The interaction of reactor antineutrinos with protons,

$$\bar{\nu}_e + p \to n + e^+, \tag{1}$$

which occurs with a momentum transfer $q \approx 0$, is, from the fundamental standpoint, one of the best areas for studying the structure of charged currents in the electroweak theory. In the standard model of the *V-A* interaction, the cross section for this reaction in the case of monoenergetic antineutrinos $\bar{\nu}_e$, $\sigma(E_\nu)$, is expressed in terms of the vector constant g_V and the axial constant g_A:

$$\sigma(E_\nu) = \frac{1}{\pi}(g_V^2 + 3g_A^2)pE\ , \tag{2}$$

where p and E are the momentum and energy of the positron, and $\hbar = c = 1$. This reaction can thus be used to determine these constants.

On the other hand, the combination of constants $(g_V^2 + 3g_A^2)$ can be determined from measurements of the decay half-life of the neutron t_n:

$$ft_n = \frac{2\pi^3 \ln 2}{m_e^5}(g_V^2 + 3g_A^2)^{-1}\ , \tag{3}$$

where $f = 1.7146 \pm 10^{-2}\%$ (Ref. 1), and m_e is the mass of the electron. Working from the experimental value $t_n = 623 \pm 12$ s, one can predict a cross section $\sigma^{V\text{-}A}$ which would be expected in a reactor experiment and then compare the result with the experimental result σ^{expt}:

$$X = \sigma^{\text{expt}} / \sigma^{V-A} = (g_V^2 + 3g_A^2)_{\nu p} / (g_V^2 + 3g_A^2)_n = t_n / t_{\nu p}\,. \tag{4}$$

According to the standard model, we would have $X = 1$. In a more general approach, $X - 1$ would evidently serve as a measure of the extent to which effects going beyond this model are being manifested. For example, if both left-hand and right-hand neutrinos can be produced in β decay, then we would have $X<1$. Since the 1970s, this possibility has been associated with a model which explains parity violation on the basis of a spontaneous breaking of an initially existing symmetry between left and right.[2-12] A deviation of X from unity may be caused, as we know, by Pontecorvo oscillations; the search for such oscillations has yet to yield a positive result (but see Ref. 3).

2. The relatively low accuracy of the measurements of σ^{expt} and the uncertainty in the calculation of the expected cross section $\sigma^{V\text{-}A}$, to which the spectrum of the reactor antineutrinos $\bar{\nu}_e$ contributes, have so far hindered an analysis of the type outlined above. On the other hand, significant progress has been made in both directions.

Afonin *et al.*[4] have reported measurements of the cross section σ^{expt} at the reactor of the Rovno nuclear power station, based on the detection of 78 000 events of reaction (1). The final results of a collaboration[5] carrying out research at the Gösgen reactor (3 000 events) and also the results of a Soviet group[6] (about 3 000 events) were published in 1986–1987. It has thus become possible to find a "worldwide average" cross section and to reduce the error to $\sigma_{\text{expt}} = \pm 3\%$, as we will see below.

The error in the value of $\sigma^{V\text{-}A}$ has also been reduced dramatically. We recall[4,5] that the cross section $\sigma^{V\text{-}A}$ (expressed in square centimeters per fission) is the convolution of the $\bar{\nu}_e$ spectrum of the reactor, $\rho(E_\nu)$, and cross section (2), corrected for recoil effects, the weak magnetism, and one-photon exchange[7,8]:

$$\sigma^{V-A} = \int \rho(E_\nu)\sigma(E_\nu)dE_\nu \pm \delta_{V-A}. \tag{5}$$

The $\bar{\nu}_e$ spectrum above the threshold for reaction (1) is formed as a result of the β decay of fragments of four fissile isotopes: ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu. We thus have $\sigma^{V\text{-}A} = \Sigma\alpha_i\alpha_i^{V\text{-}A}$, $\Sigma\alpha_i = 1$, where the α_i are the contributions of these isotopes. The sum of the contributions of ^{235}U and ^{239}Pu is more than 85%.

The improvement in accuracy is achieved because a method was found to reconstruct the $\bar{\nu}_e$ spectrum from the spectrum of the β electrons which are fission fragments[9,10]; for the most abundant isotopes (^{235}U and ^{239}Pu), these β spectra have been measured highly accurately.[11] It is important to note that Afonin *et al.*[4] and Zacek *et al.*[5] used the same spectra in their analyses.

The expected cross sections $\sigma_i^{V\text{-}A}$ expressed in units of 10^{-43} cm^2/fission) are $6.31 \pm 3.5\%$ (^{235}U), $4.11 \pm 3.5\%$ (^{239}Pu), $8.83 \pm 10\%$ (^{238}U), and $6.32 \pm 10\%$ (^{241}Pu). The relative error in the cross section $\sigma^{V\text{-}A}$ in Ref. 4, for the actual fuel compositions, was estimated to be $\delta_{V\text{-}A} = 3.7\%$. This figure includes the error δ_{sp}, which stems from the uncertainty in the spectrum, and also the error δ_t, which reflects the uncertainty in our knowledge of the decay half-life of the neutron.

Consequently, the value of $\sigma^{V\text{-}A}$ in each experiment is found for the particular isotopic composition of the nuclear fuel, so the value of X in (4) is independent of this composition. We state for definiteness that for reactors of a common type, e.g., those at Gösgen and Rovno, the actual differences in $\sigma^{V\text{-}A}$ do not exceed 2–3%.

3. Let us examine the results found in Refs. 4–6.

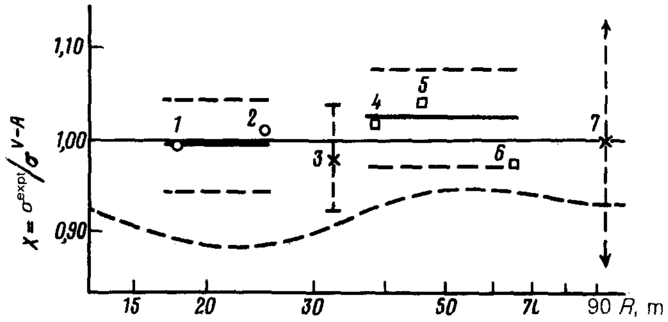

FIG. 1. The ratio (X) of the measured cross section (σ^{expt}) and the expected cross section ($\sigma^{V\text{-}A}$) for reaction (1). The quantity plotted along the abscissa is the distance from the center of the reactor core (in meters) at which the measurements were carried out. 1,2—Reference 4; 4–6—Ref. 5; 3,7—Ref. 6. The dashed lines show only the errors δ_{expt}. The error in $\sigma^{V\text{-}A}$ is estimated to be $\delta_{V\text{-}A} = 3.7\%$. The dashed curve is the $X(R)$ dependence expected in the case of oscillations with the parameter values $|m_1^2 - m_2^2| = 0.2$ eV^2 and $\sin^2 2\theta = 0.15$.

Reference 4. Two different detectors—a scintillation spectrometer and an integral detector—at a distance of 18.1 m from the center of the reactor core measured $\sigma^{\text{expt}} = 5.6\times 10^{-43}$ cm^2/fission $\pm 4.6\%$ and $X = 0.995 \pm 4.6\%$. The ratio of the cross sections at distances of 25.2 m and 18.1 m was also measured: $\sigma^{\text{expt}}(25)/\sigma^{\text{expt}}(18) = 1.013 \pm 4\%$ (see points 1 and 2 in Fig. 1; the dashed lines indicate the errors).

Reference 5. A scintillation spectrometer was used to carry out three successive measurements, at distance of 37.9, 45.9, and 64.7 m from the reactor. The results are $X = 1.018 \pm 2.4\% \pm 4.8\%$, $X = 1.045 \pm 2.4\% \pm 4.8\%$, and $X = 0.975 \pm 4.7\% \pm 4.8\%$, where the first error is the error of the given measurement which is uncorrelated with the other errors, while the second error (4.8%) is the overall methodological error, which includes errors in the reactor power, the detection efficiency, and so forth (points 4–6 in Fig. 1).

Reference 6. A single integral detector was used. It detected the antineutrinos $\bar{\nu}_e$ from two reactors at distances of 32.8 m and 92.3 m. The results are $\sigma^{\text{expt}} = 6.19\times 10^{-43}$ cm^2/fission $\pm 5.8\%$ and $\sigma^{\text{expt}} = 6.3\times 10^{-43}$ cm^2/fission $\pm 20\%$. Vidyakin *et al.*[6] referred the cross sections to the $\bar{\nu}_e$ spectrum of ^{235}U (points 3 and 7 in Fig. 1).

Only the experimental errors in the values of X have been indicated here.

4. We can draw certain conclusions, first without considering the hypothesis of neutrino oscillations.

It can be seen from Fig. 1 that the results attained in the different studies agree very well with each other, so an averaging can be carried out. After we take this average, we find the basic result

$$X = \sigma^{\text{expt}} / \sigma^{V-A} = 1.002 \pm 3\% \pm 3.7\% , \qquad (6)$$

where the first error refers to σ^{expt}, and the second to $\sigma^{V\text{-}A}$.

A. It follows from (4) and (6) that the characteristics of reaction (1) and the β decay of the neutron agree with each other within the framework of $V-A$ theory:

$$(g_V^2 + 3g_A^2)_{\nu p} / (g_V^2 + 3g_A^2)_n = t_n/t_{\nu p} = 1.002 \pm 4.7\,\%. \tag{7}$$

For weak interactions, this appears to be the most precise test of the equality of the probabilities for reactions which go in different channels of the same diagram. Using the value[1] $g_V = (1.4127 \pm 0.0003) \times 10^{-49}$ erg·cm^3, we find

$$g_A^{\nu p} = 1.78 \times 10^{-49}\ \text{erg·cm}^3 \pm 2.6\,\%. \tag{8}$$

Noting that we have[1,5] $(g_V^2 + 3g_A^2)^{1/2} = 3.394 \times 10^{-49}$ erg·cm^3 for the decay of the neutron, we find

$$g_A^{\nu p} / g_A^n = 1.00 \pm 2.8\,\%, \qquad t_{\nu p} = 622\ \text{c} \pm 4.4\,\%. \tag{9}$$

The results in (8) and (9) are improvements on the estimates found in Ref. 4.

B. The absolute value of the cross section for inverse β decay corresponding to the isotopic mixture of 60.6% ^{235}U, 27.6% ^{239}Pu, 7.5% ^{238}U, and 4.3% ^{241}Pu is

$$\sigma^{\text{expt}} = 5.90 \times 10^{-43}\ \text{cm}^2/\text{fission} \pm 3\,\%. \tag{10}$$

Using $\sigma_i^{V\text{-}A}$ from Sec. 2, we can convert this cross section to correspond to a nuclear fuel of a different composition, in particular, to ^{235}U:

$$\sigma^{\text{expt}}(^{235}\text{U}) = 6.32 \times 10^{-43}\ \text{cm}^2/\text{fission} \pm 3.3\,\%. \tag{11}$$

C. If we assume that antineutrinos $\bar{\nu}_e$ of both helicities can be produced in β decay and thus absorbed in reaction (1), we conclude that we must replace relation (4) by $X = 1/2\ (1 + h_\nu^2)$, where h_ν is the polarization of the $\bar{\nu}_e$, according to simple balance considerations. From (6) we then find

$$h_\nu = 1.00 \pm 4.7 \times 10^{-2}. \tag{12}$$

This is an improvement on the estimate of Ref. 12, where the question was analyzed in terms of the model of Ref. 2.

D. The analysis of Refs. 4–6 revealed no effects which could be attributed to neutrino oscillations. Here it is pertinent to consider only the limiting case of large mass parameters. In this case we find $\sigma^{\text{expt}}/\sigma^{V\text{-}A} = 1 - 1/2 \sin^2 2\theta$, where θ is the mixing angle of the neutral leptons with masses m_1 and m_2. From (6) we then find

$$\sin^2 2\theta \leqslant 9.4 \times 10^{-2}\ (68\,\%\ \text{C.L.})\ \text{for}\ |m_1^2 - m_2^2| > 2\ \text{eV}^2. \tag{13}$$

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